Model Reference Adaptive Control (MRAC) Experiment Description (Curt Hanson)

Flight Test Objectives

- **Flight Test a Simplified Adaptive Controller**
  - Investigate the relationship between the complexity and utility of adaptive controls
  - Demonstrate, in a flight environment, the strengths and weaknesses of a simple “textbook” model reference adaptive controller
  - Provide experimental evidence supporting the need for, and benefits of, additional complexity

- **Investigate Pilot Interaction with Adaptive Systems**
  - Gather evidence in support of the following questions:
    - Should an adaptive controller be active at all times or only in emergencies?
    - Should an adaptive controller be a “one size fits all” solution, or should it be tailored to the emergency situation?
  - Determine whether the pilot has sufficient information to customize the adaptive controller
  - Identify any potentially adverse interaction between the pilot and the adaptive controller

Experiment Background

Experiment Selection Process:

2009, Apr: The IRAC project disseminated a request for information (RFI) on potential flight experiments to the adaptive controls community

2009, Aug: The IRAC project hosted a workshop to discuss the RFI and responses from Industry, Academia and Government

2009, Sep: A decision letter was released outlining the IRAC project's research focus for flight experiments on the 853 testbed (FAST):

MRAC Objectives

Primary
1. Experiments focused on the design and evaluation of simple yet effective adaptive algorithms, that may be more compatible with existing verification and validation techniques.

Secondary
2. Experiments that investigate methods to include pilot control, awareness, and interaction with the adaptive control algorithm.

Out of Scope
3. Experiments that address issues associated with the constraints imposed by both static load and dynamic structural interaction.

“simple yet effective” Adaptive Control

<u>Nonlinear Dynamic Inversion</u> *plus* <u>Model Reference Adaptive Control</u>

Nonlinear Dynamic Inversion

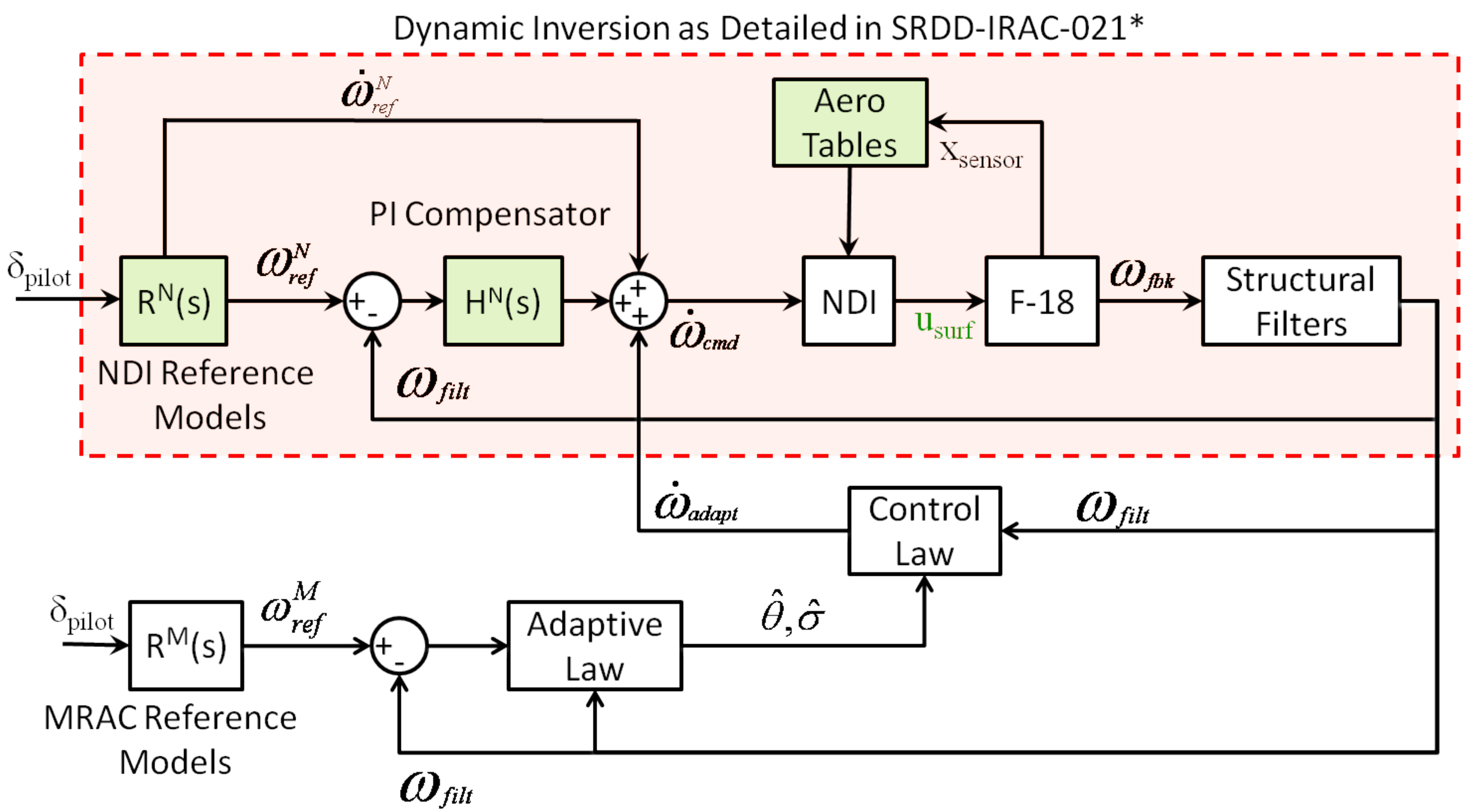
- Explicit Model Following
  - integrates nicely with many adaptive control techniques, such as model reference adaptive control
- Failure Modeling
  - The NDI controller can be used to model a variety of failure dynamics
- Analyzability
  - The NDI architecture is easy to analyze and include in stability proofs
- Open-Source Architecture
  - By specifying non-ITAR reference models, simulation and flight test data can be openly published
- Ease of Gain Scheduling
  - The NDI architecture implicitly accomplishes gain scheduling via its suite of aerodynamic coefficient lookup tables

Model Reference Adaptive Control

- Basic
  - easy to understand and implement
  - well-known throughout the community
- Generic and Extensible
  - forms the basis of more advanced algorithms
  - easy to add modification terms to the update laws
    - normalization, projection, e-mod, etc
- Aligns with NASA Experience Base
  - Past work on IFCS (T/N 837)
  - Recent work at ARC
- Meets Kalmanje Krishnakumar’s Directives:

1. Don’t showcase someone’s favorite adaptive controller, and
2. Don’t compare multiple control schemes

Control Architecture



* -Failure implementation capabilities have been add to the items in green which differ from the design in SRDD-IRAC-021

Theoretical Background

1. <u>Desired (Reference Model) Dynamics</u>

$$\dot{x}_m = A_m x_m + B_m r$$

2. <u>Uncertain Plant Dynamics</u>

$$\dot{x} = Ax + Bu + \sigma$$

where $A = A_m + B_m \theta^T$

$B = B_m$

$$\dot{x} = \underbrace{\left(A_m + B_m \theta^T\right)}_{\text{matched uncertainty}} x + \underbrace{B_m u + \sigma}_{\text{unmatched uncertainty}}$$

3. <u>Adaptive Parameter Estimation</u>

$$\left.\begin{aligned} \dot{\hat{\theta}} &= \Gamma_\theta e^T P B_m x \\ \dot{\hat{\sigma}} &= -\Gamma_\sigma e^T P B_m \end{aligned}\right\} \text{Lyapunov-based adaptive update laws}$$

where $e = x_m - x$

4. <u>Control Signal</u>

$$u = r + \hat{\theta}^T x - \hat{\sigma}$$

5. <u>Closed-Loop Dynamics with Adaptive Control</u>

$$\dot{x} = A_m x + B_m r + B_m \left(\theta^T + \hat{\theta}^T\right) x + \left(\sigma - B_m \hat{\sigma}\right) \Rightarrow \underbrace{\dot{x} = A_m x + B_m r}_{\text{if } \hat{\theta}^T \to -\theta^T \text{ and } B_m \hat{\sigma} \to \sigma}$$

Controller Configurations

Configuration*	Strengths	Weaknesses
Simple MRAC (sMRAC) $\begin{bmatrix} \overset{\sim 0}{\dot{\hat{\theta}}_1} \\ \dot{\hat{\theta}}_2 \end{bmatrix} = \Gamma_\theta \begin{bmatrix} \int e \\ e \end{bmatrix}^T PB_m \begin{bmatrix} \int q \\ q \end{bmatrix}$	one input and one adaptive parameter	over-adaptation, no unmatched uncertainty term
MRAC w/ Normalization and Optimal Control Modification (onMRAC) $\begin{bmatrix} \overset{\sim 0}{\dot{\hat{\theta}}_1} \\ \dot{\hat{\theta}}_2 \end{bmatrix} = \frac{\Gamma_\theta}{1 + R_\theta q^2} \left(\begin{bmatrix} \int e \\ e \end{bmatrix}^T PB_m \begin{bmatrix} \int q \\ q \end{bmatrix} - \nu \hat{\theta}_2 B_m^T P A_m^{-1} B_m q^2 \right)$	suppresses over-adaptation	no unmatched uncertainty term
onMRAC plus Unmatched Uncertainty (onMRAC+) $\dot{\hat{\sigma}} = \frac{-\Gamma_\sigma}{1 + R_\sigma q^2} \begin{bmatrix} \int e \\ e \end{bmatrix}^T PB_m$	suppresses over-adaptation, better performance with unmatched uncertainties	reduced performance with matched uncertainties

***Pitch-Axis Examples Shown**

Simulated In-Flight Failures

Failure	Failure Magnitude	Comments
1. Reduced pitch damping	80% reduction	not maneuverable in NDI due to slowly divergent, oscillatory instability
2. Reduced roll damping	117% reduction	PIO-prone with NDI
3. Reduced pitch static stability	60% reduction	slow pitch-up transient on failure insertion
4. Frozen left stabilator	100% failed	similar to RFCS right stabilator failure
5. Roll-to-pitch input coupling	dep+1.0*dap	prone to causing over-adaptation of sMRAC configuration

simulated failures are faded in/out over 2 seconds

Special Features, Part 1

Pedal Suppression Gain

Symptom: Sudden un-commanded rolls were observed following extended SSHS maneuvers

Cause: Over-adaptation due to non-zero roll stick accompanied by zero roll rate (i.e. high roll error)

Fix: Roll adaptation is linearly scaled from 100% to 0% over the first 50 lbs of rudder pedal, and held at zero out to max pedal

High-Pass Filtering of Pitch Rate to Adaptive Laws

Symptom: Over-adaptation of onMRAC and onMRAC+ configurations during 2.5g windup turns, reduced pitch damping failure

Cause: Oscillations about a non-zero pitch rate caused pitch adaptive parameter to “un-adapt”; exacerbated by normalization term

Fix: High-pass filtering of the pitch rate used in the adaptive update law

Special Features, Part 2

Time-Correlation of Error Calculation

Symptom: Poor performance and low time delay margins

Cause: Time delay differences between reference signals and measured feedback signals cause “phantom” error, leading to inappropriate adaptation

Fix: The reference signals to the error calculation are delayed by 8 minor (160 Hz) frames:

- 2: known system time delays
- 3: approximate phase loss due to anti-aliasing filter
- 3: an empirically-determined amount of additional delay

Nosewheel Steering (NWS) Logic

PVI Display

‘N’: NDI control

‘S’: simple MRAC

‘O’: MRAC with normalization / optimal modification term

‘+’: MRAC with normalization / optimal modification term and unmatched uncertainty term

‘=‘: adaptive parameters are frozen

‘X’: invalid DAG/CAT

Notes

1. when the failure is inserted, the PVI character will flash
2. removal of adaptation is rate-limited for transient suppression

ARTS is Engaged

1st Press: Inserts Failure

2nd Press : Turns on Adaptation

3rd Press: Freezes Adaptation

4th Press: Unfreezes Adaptation

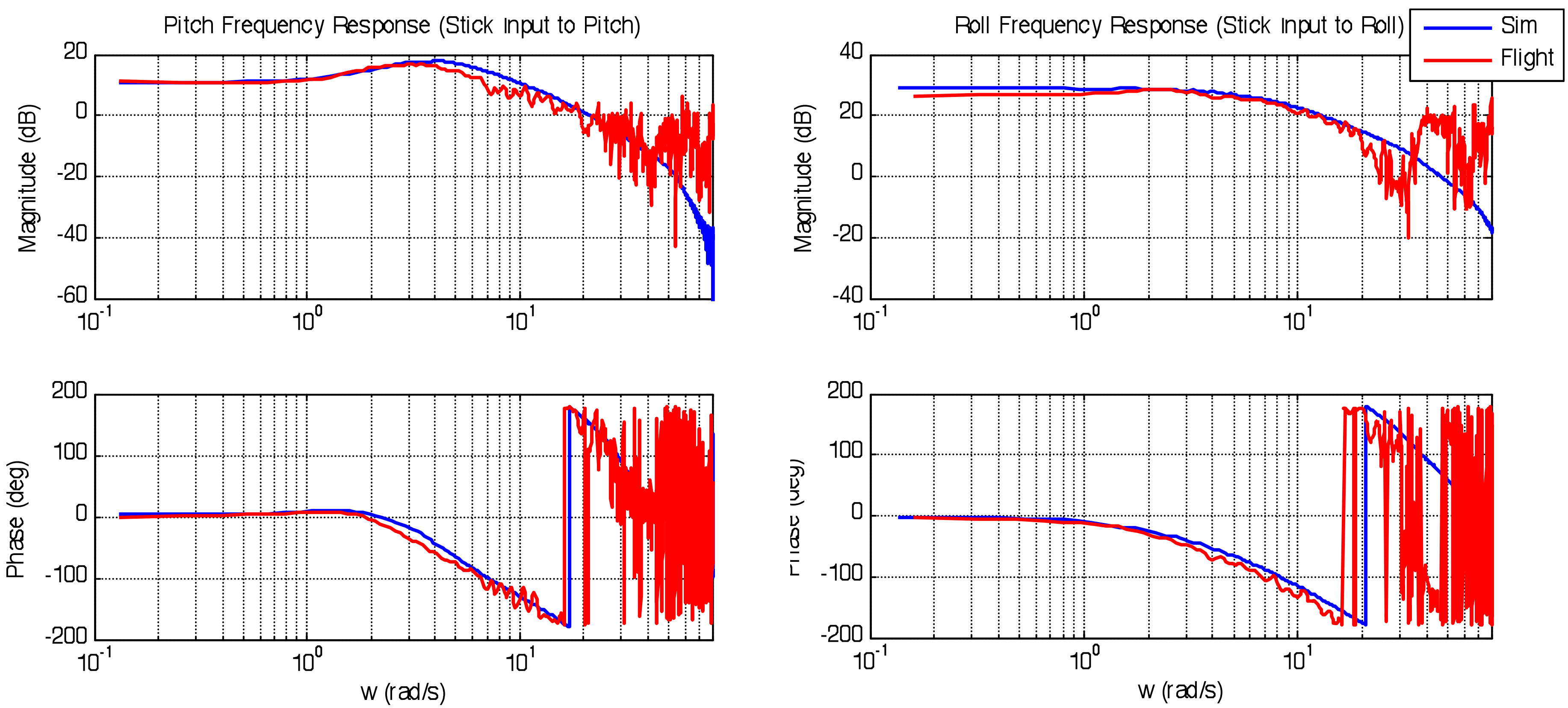
5th Press: Removes Failure

6th Press: Turns off Adaptation (reset counter)

De-bounce:
The NWS logic contains a 400ms de-bounce to avoid repetitive annunciations of the NWS button

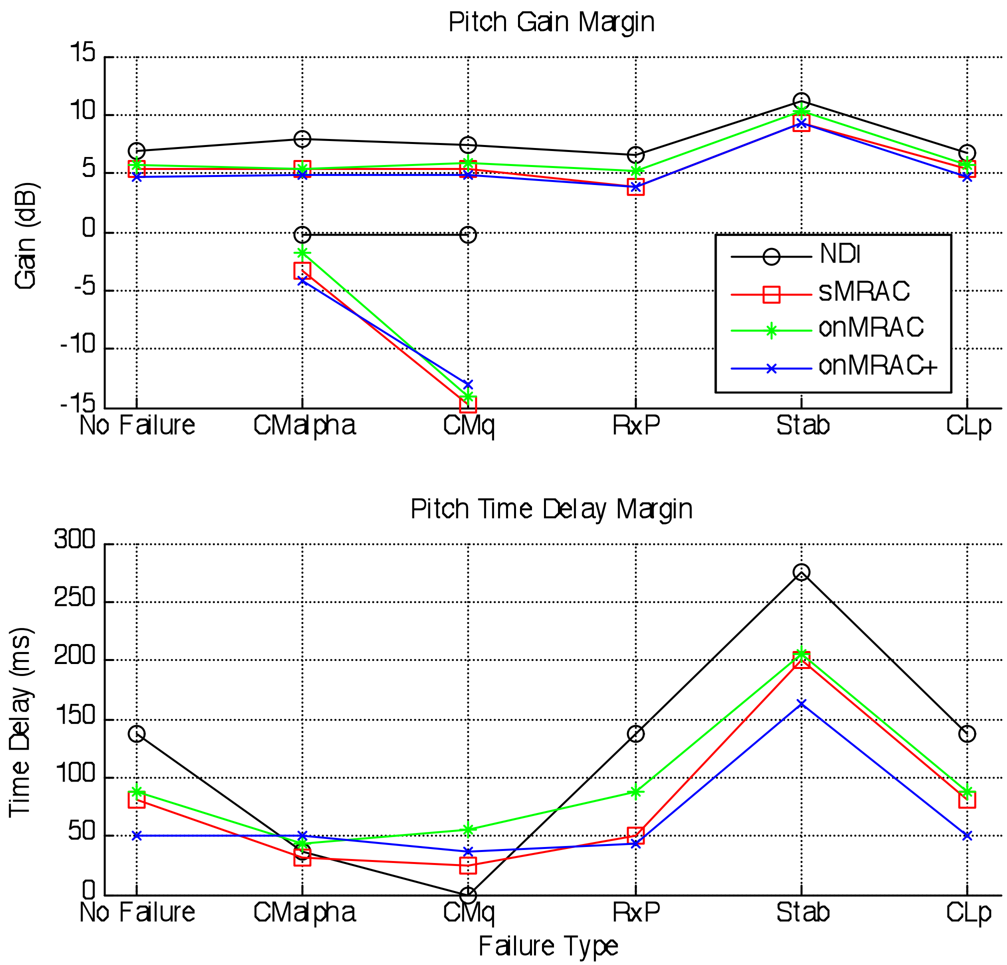
Simulink Toolset

Comparison of flight data to the Simulink toolset that was used for analysis.



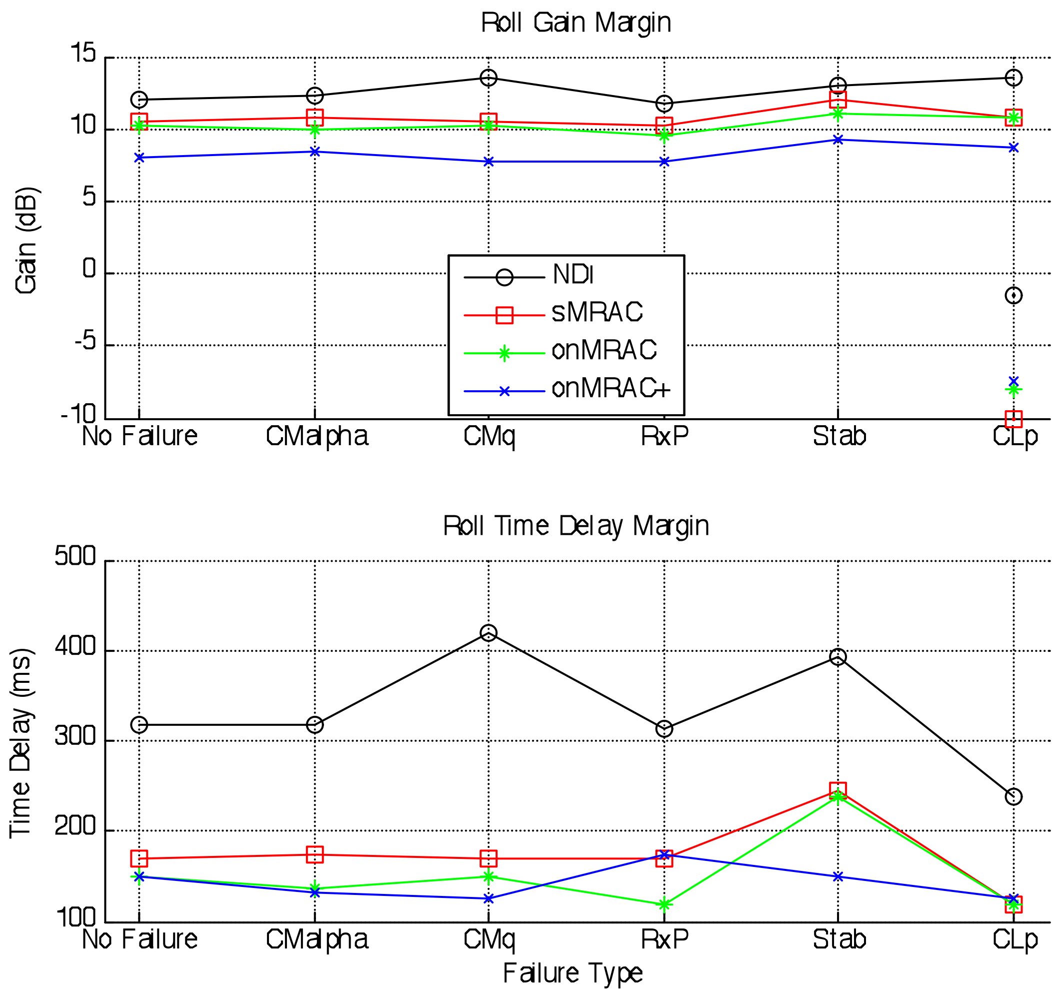
*** Flight Data: NDI v1.4 at FC6 (Flight 112)**

Results – Robustness (Pitch)



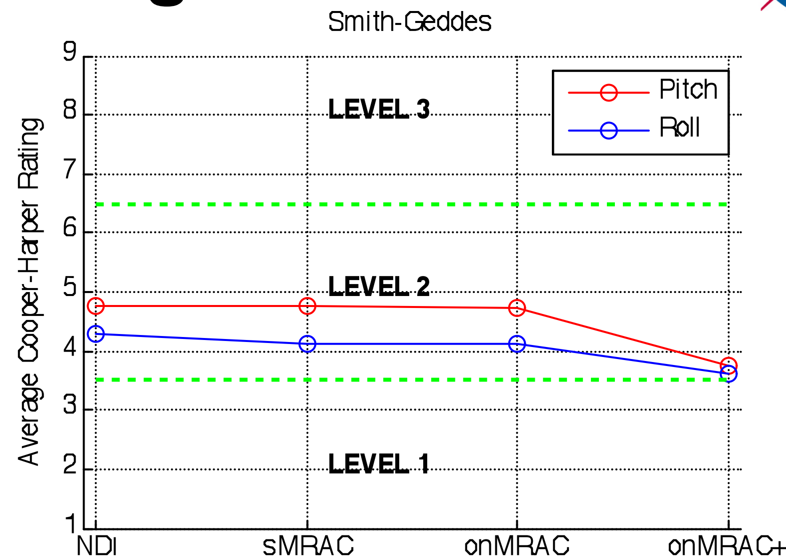
*** Includes all known delays**

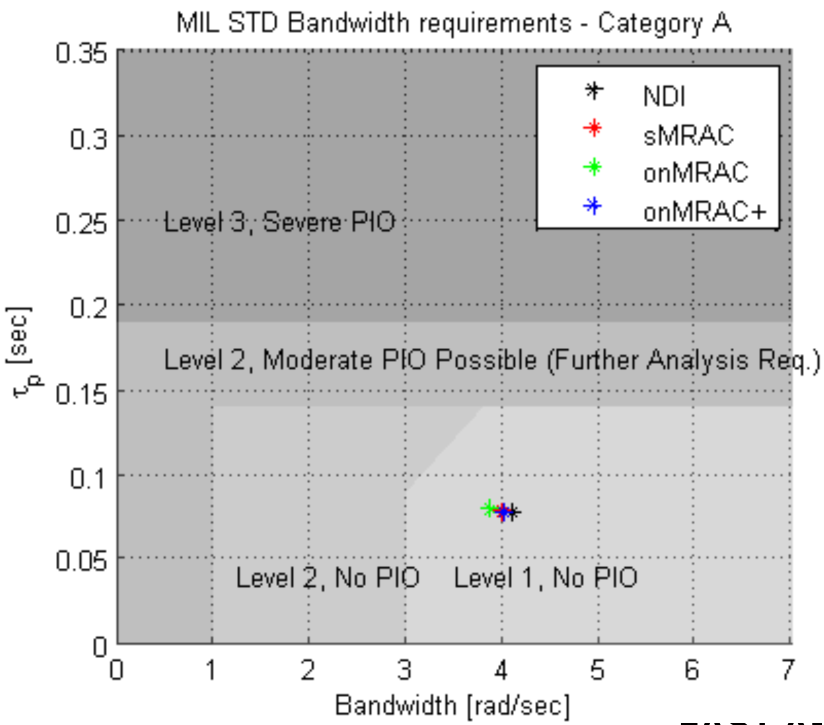
Results – Robustness (Roll)

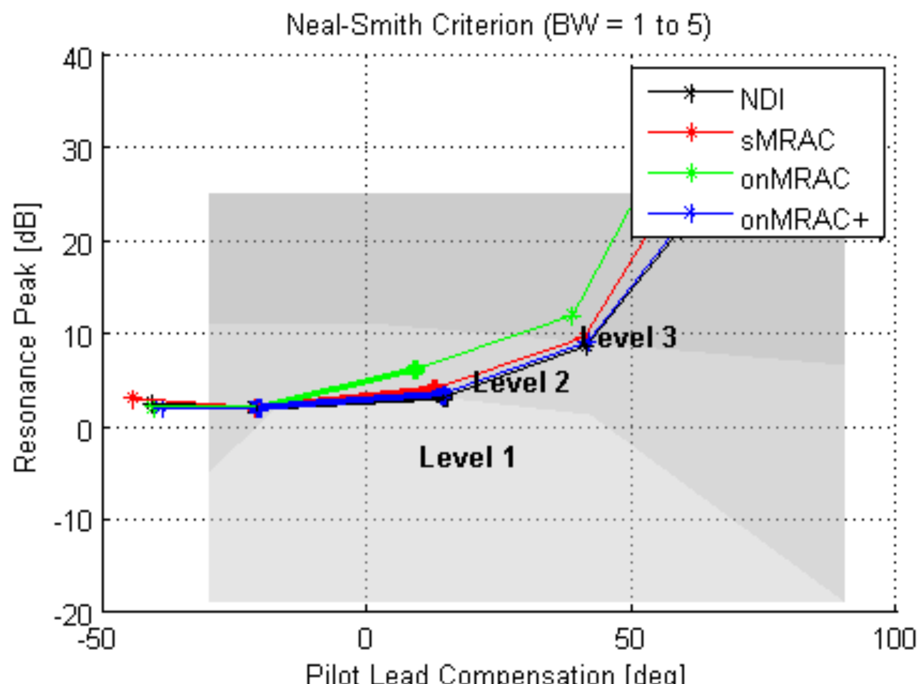


No Failure Handling Qualities

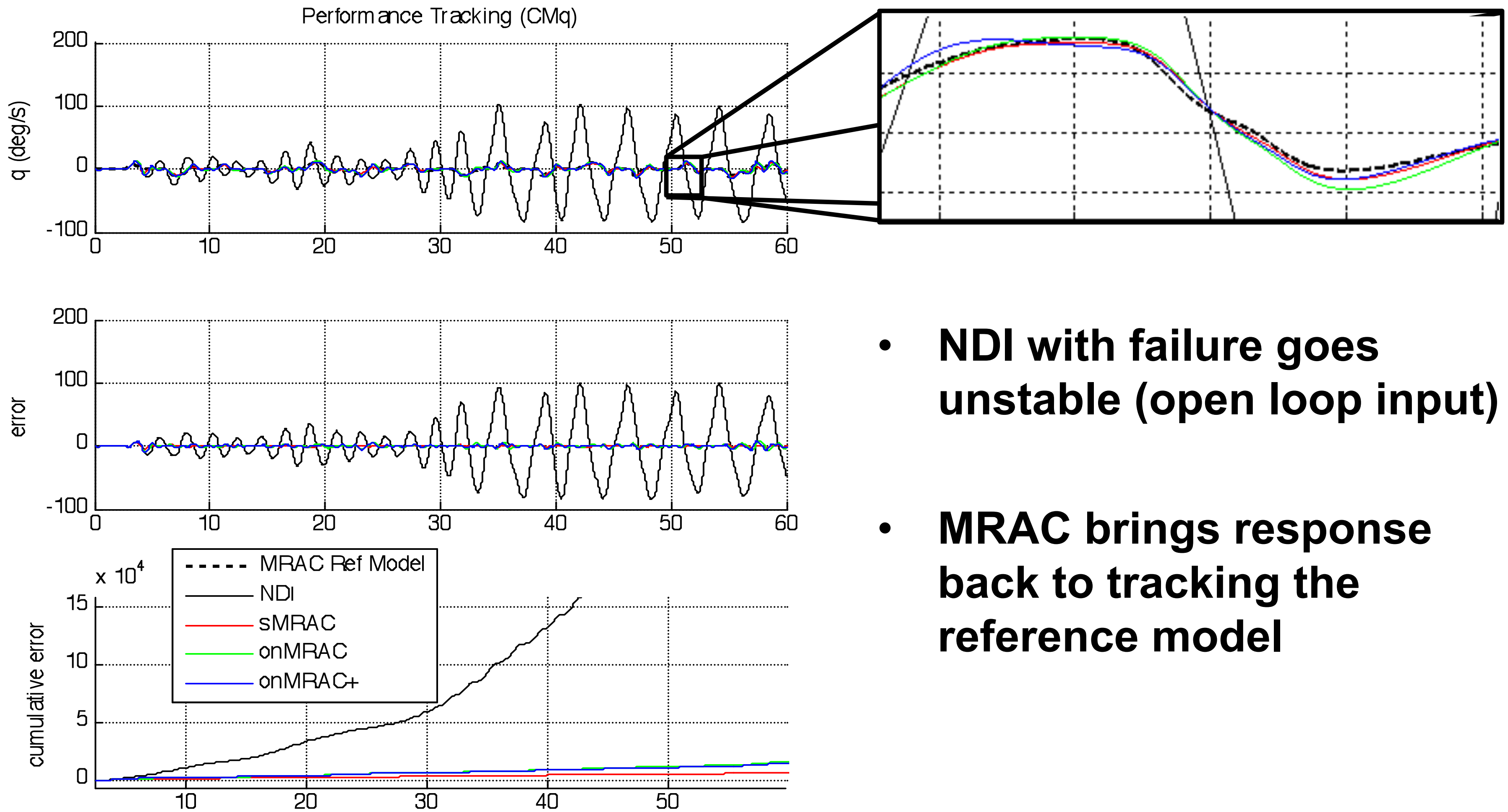
- **Level 1 to 2**
- **MRAC remains near baseline NDI handling qualities.**





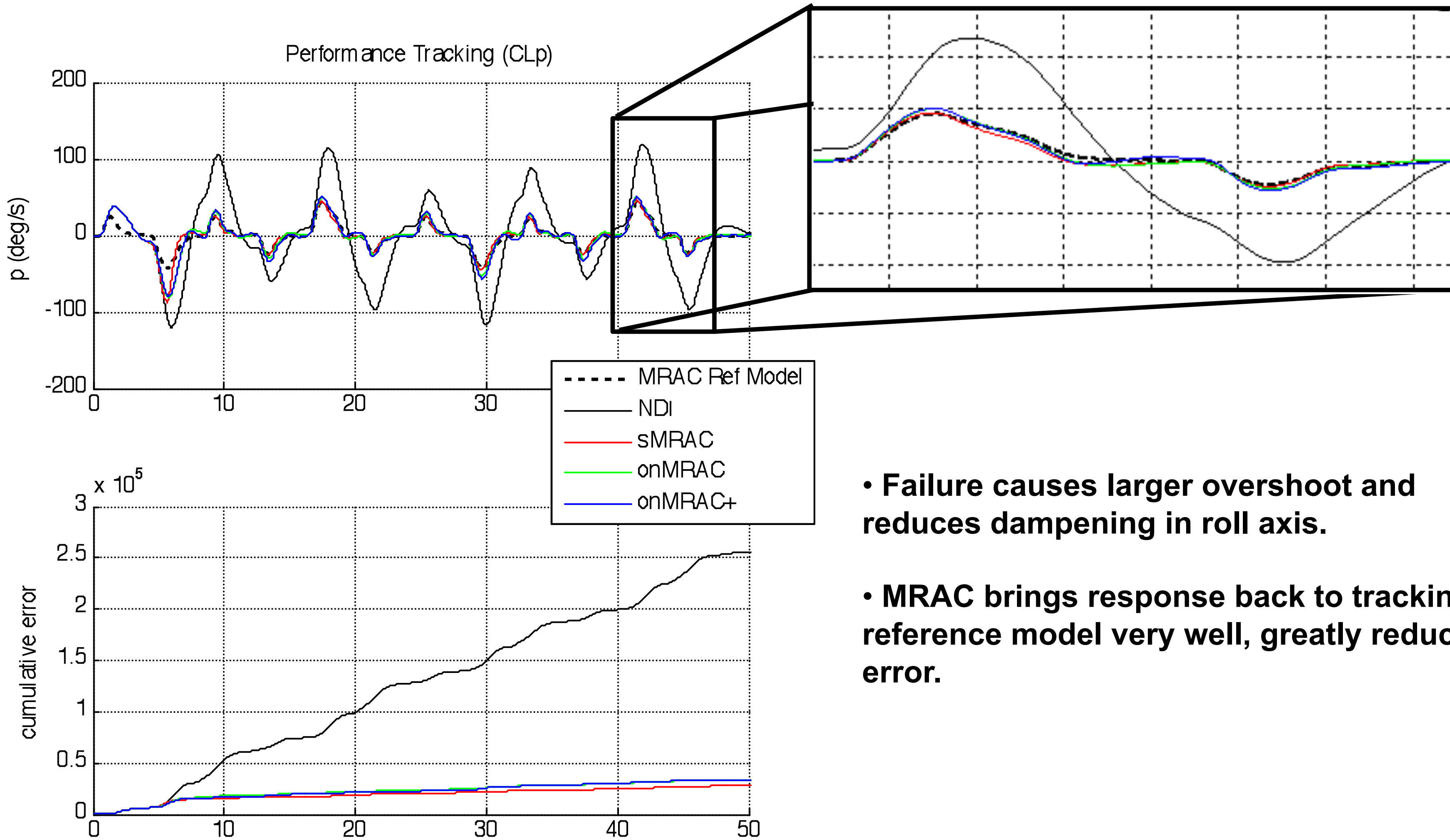


C_{Mq} Failure Performance



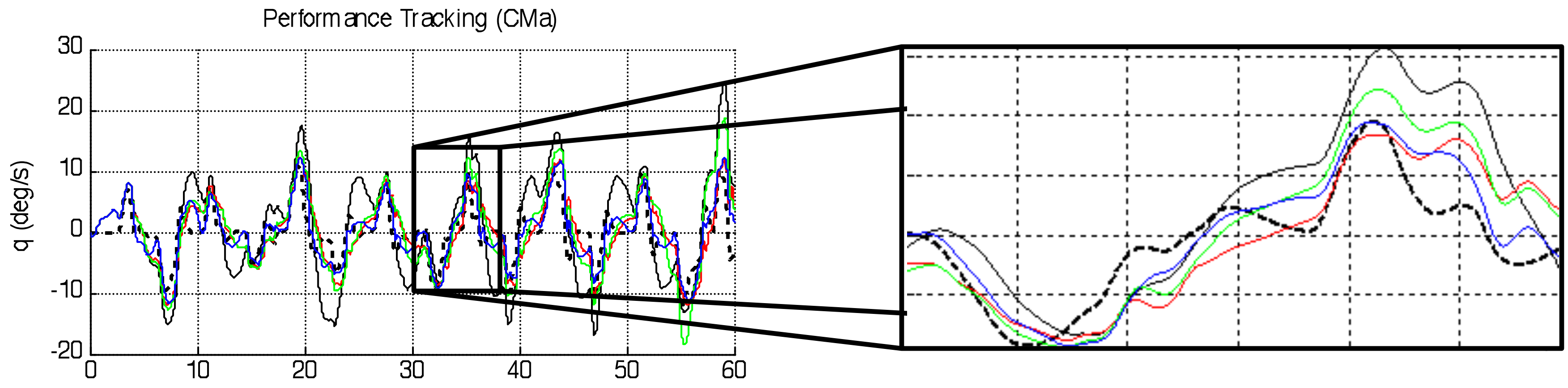
- **NDI with failure goes unstable (open loop input)**
- **MRAC brings response back to tracking the reference model**

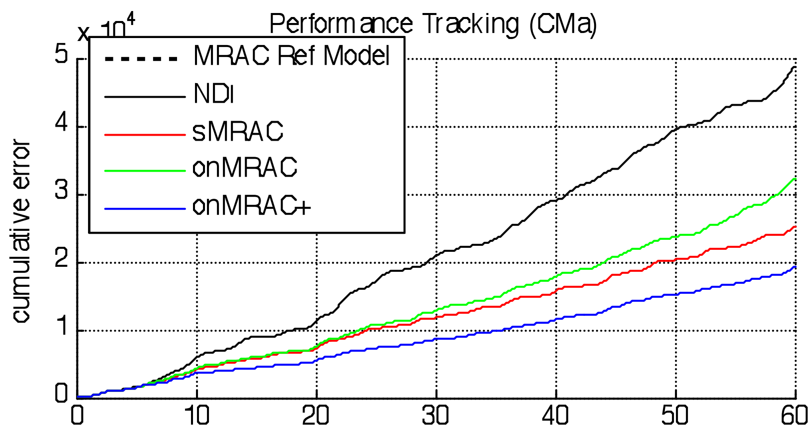
C_{L_p} Failure Performance



- **Failure causes larger overshoot and reduces dampening in roll axis.**
- **MRAC brings response back to tracking reference model very well, greatly reduces error.**

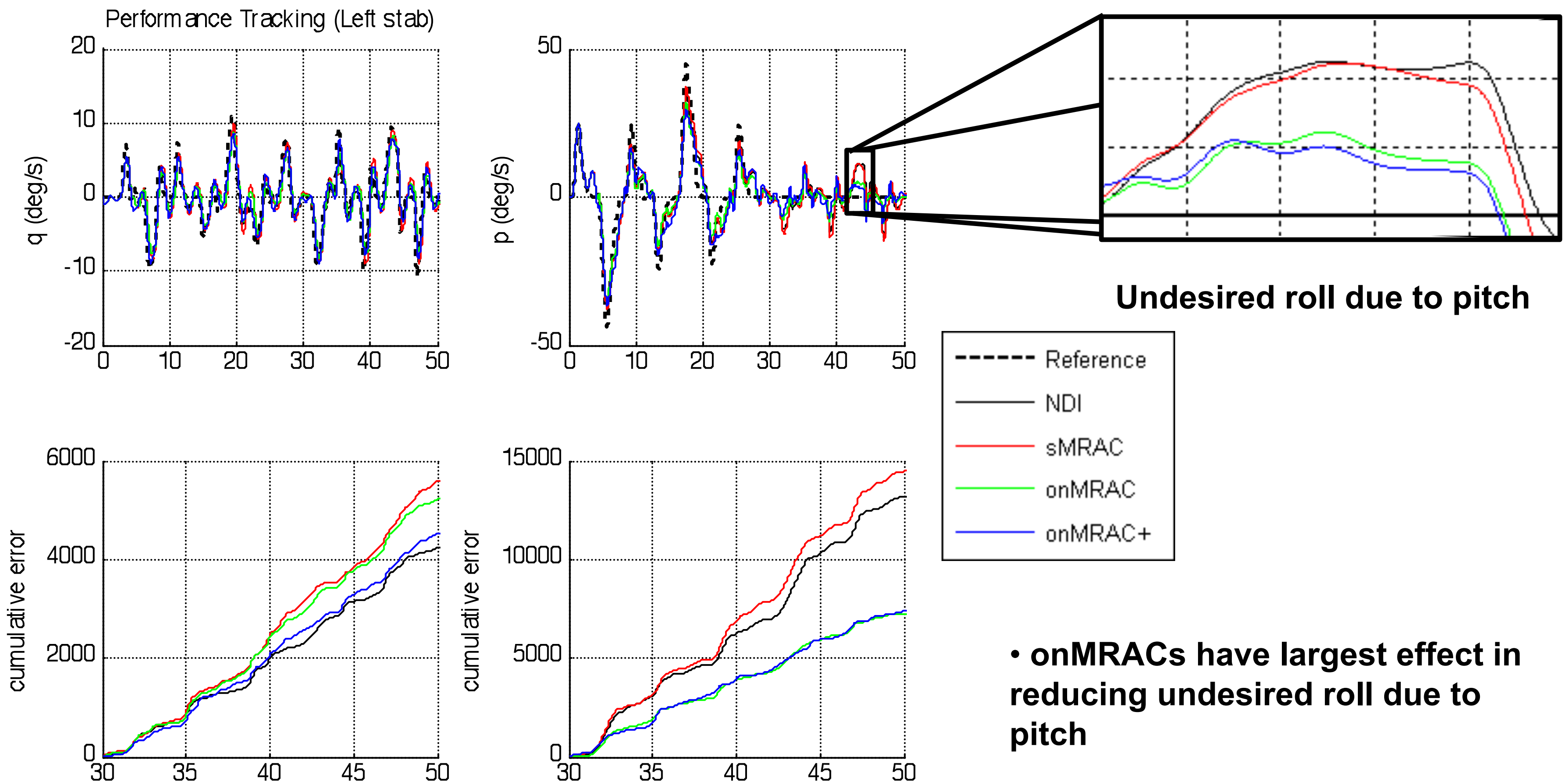
$C_{M\alpha}$ Failure Performance





•MRAC improve response from the NDI but response does not track reference model very well.

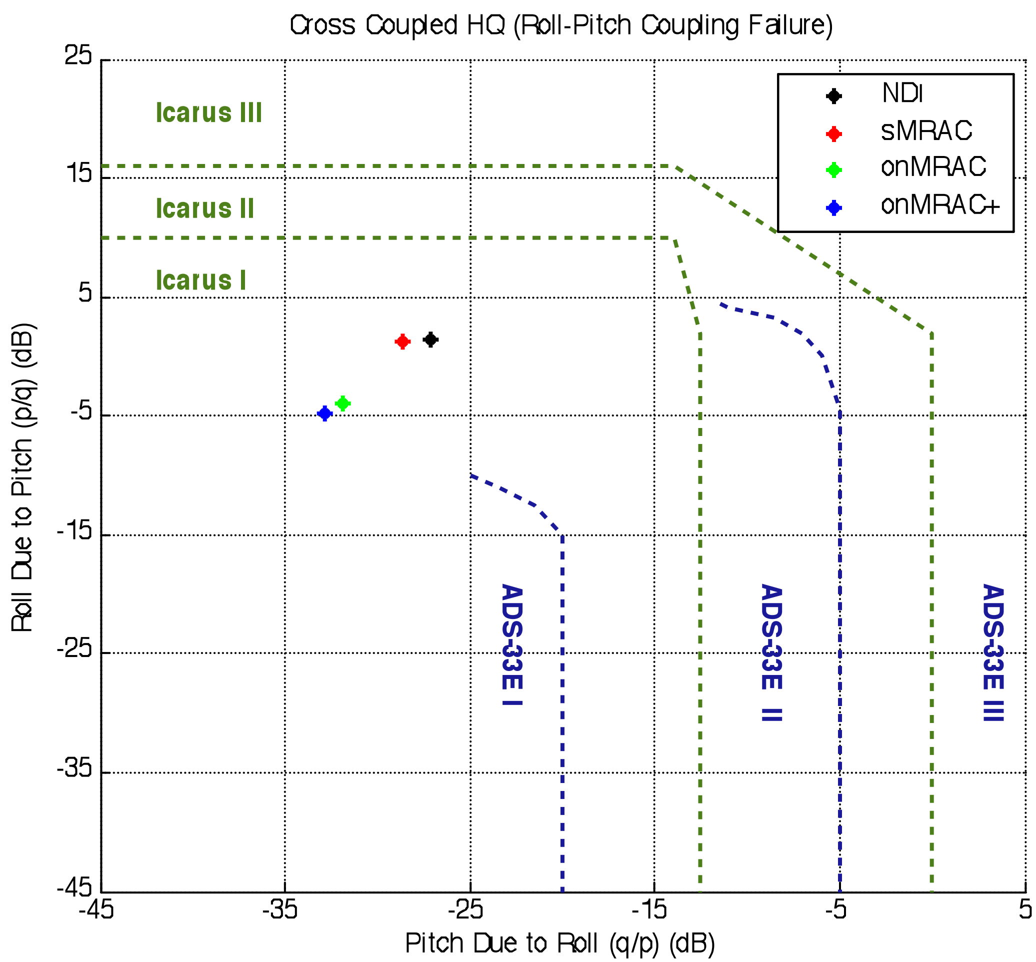
Stab Failure Performance



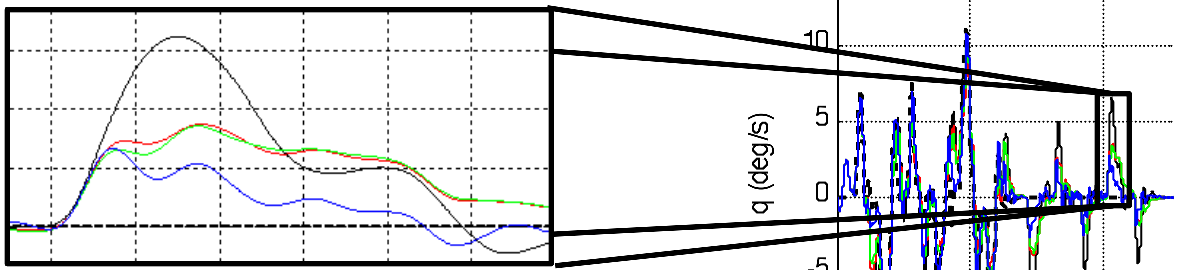
Undesired roll due to pitch

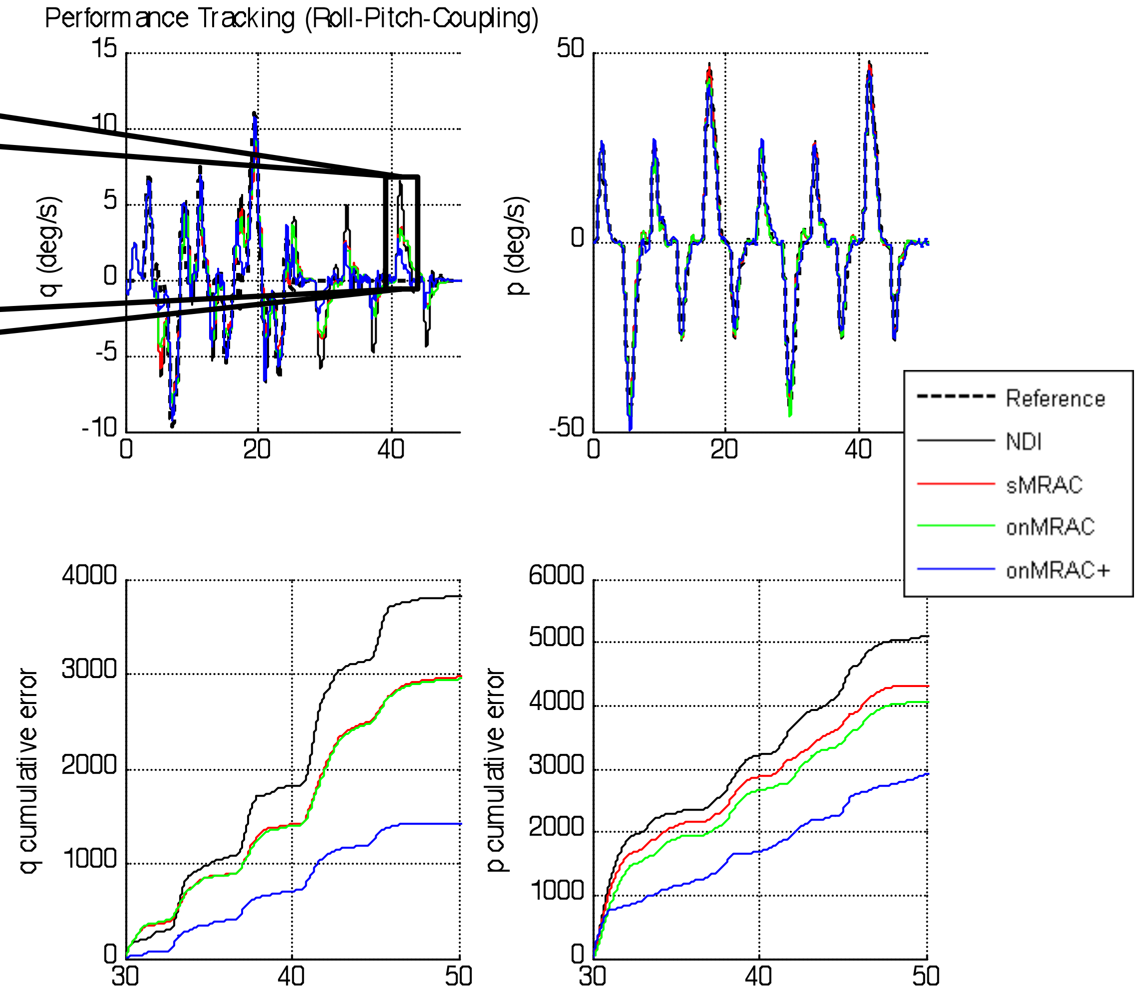
- onMRACs have largest effect in reducing undesired roll due to pitch
- Slightly worse pitch performance but in line with nonfailed performance.

Stab Failure Handling Qualities



Roll to Pitch Coupling Performance





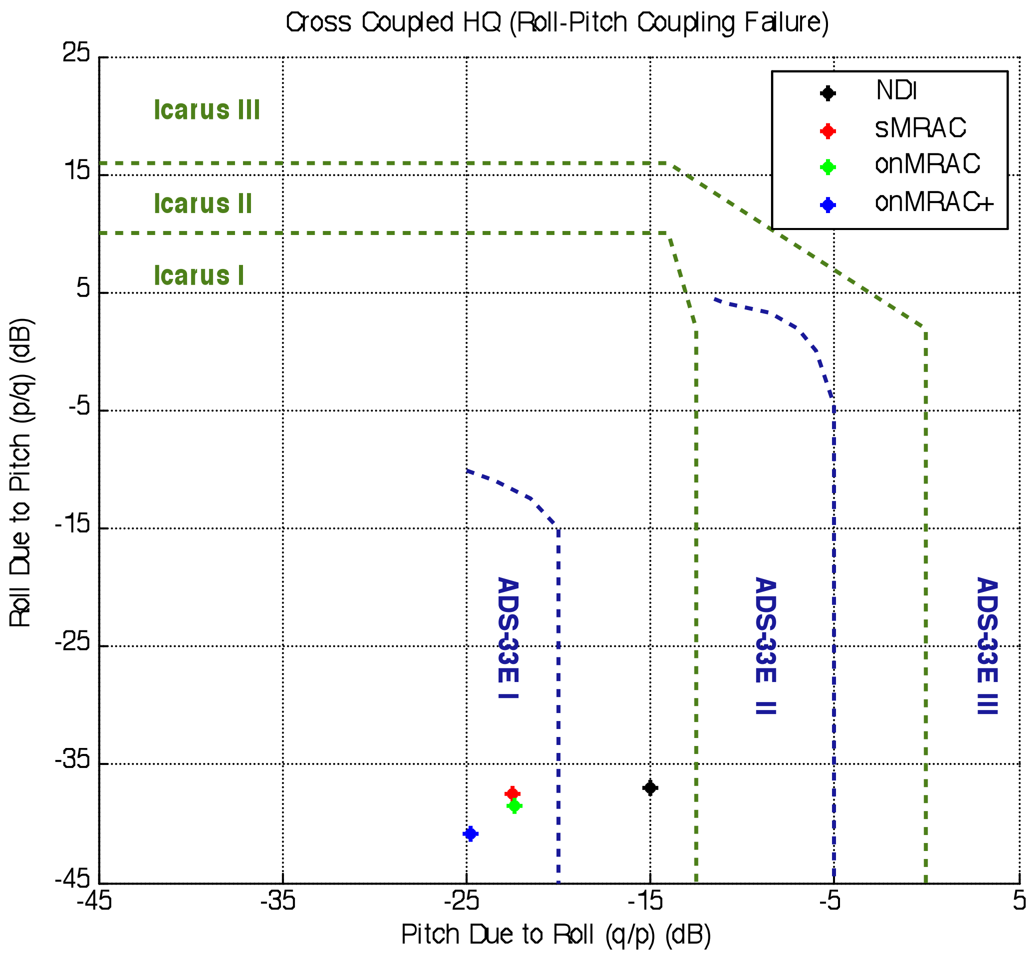
- MRAC reduces the pitch response due to roll.

- Also improves roll tracking.

Roll to Pitch Coupling Handling Qualities

• sMRAC and onMRAC reduce (q/p) by nearly half.

• onMRAC+ reduces undesired pitch due to roll down to 1/3 of that of the NDI



Summary

- **Experiment Meets Requirements**
  - **Minimal impact in the no-failure cases**
  - **The minimal gain and time delay margins are met for all adaptive controllers with no failures**
  - **The adaptive controller improves tracking response with failures**
  - **Without adaptation, failures are either controllable by the pilot or slowly divergent**
- **Adaptation meets the experiment objectives**
  - **Failures are sufficiently aggressive to show the benefits of adaptation**
  - **Demonstrates a tradeoff between simplicity and versatility**